Fragment penetration in composite plates

PML 1999-B23

TNO Prins Maurits Laboratory

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Ir. E. van Meerten
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TNO-rapport **PML 1999-B23**

Probleemstelling
Toekomstige generaties vliegtuigen en helikopters zullen in toenemende mate gebruikmaken van composieten als constructiemateriaal. De thans gehanteerde methodologie om kwetsbaarheidsstudies uit te voeren voldoet goed zolang het constructies betreffen bestaande uit metaallegeringen. Het ballistisch weerstandsgedrag van composieten in vliegtuigconstructies is tot nu toe een vrijwel onbekend terrein. Teneinde in de toekomst ook kwetsbaarheidsstudies van dergelijke vliegtuigen/helikopters uit te kunnen voeren, is een begin gemaakt om het penetratiegedrag van scherven door composieten nader te bestuderen.

Beschrijving van de werkzaamheden
In samenwerking met het Nationaal Lucht- en Ruimtevaartlaboratorium en met de Defense Evaluation & Research Agency/Farnborough (UK) zijn composietplaten, die representatief zijn voor de buitenhuid van een vliegtuig, aangeschaft teneinde hierop schietproeven met (simulatie)scherven uit te voeren. Doel van deze schietproeven was om zogenaamde penetratierelaties tussen trefsnelheid en restsnelheid direct na penetratie vast te leggen als functie van materiaaldikte, trefhoek, materiaalsoort en scherfmassa en -vorm. Teneinde de hoeveelheid aan meetgegevens te complementeren zijn tevens schietproeven uitgevoerd op composietplaten die mogelijk gebruikt kunnen worden aan boord van schepen ter bescherming van cruciale onderdelen zoals bijvoorbeeld de radarmast van een fregat.

Resultaten en conclusies
De ballistische weerstand van de drie geteste composieten is vergeleken met aluminium en stalen platen van gelijke dikte. Voor een trefsnelheid van 1000 m/s kan de ballistische weerstand van een composietplaat met een bepaalde plaatdikte vergeleken worden met een aluminium plaat van ongeveer 55-60% van die plaatdikte en met een stalen plaat van ongeveer 20-25% van die plaatdikte.

Toepasbaarheid
De schietproeven hebben voldoende gegevens opgeleverd om meer onderbouwd het penetratiegedrag van scherven door composieten te modelleren en te gebruiken voor kwetsbaarheidsstudies aan toekomstige generaties vliegtuigen en helikopters.

Vervolgonderzoek
Een volgende stap in dit onderzoek zou moeten zijn om de aangebrachte schade aan de composieten te kwantificeren en deze te vertalen naar de reststerkte van de constructie. Dit aspect is nog niet meegenomen in het kwetsbaarheidsonderzoek.

Defensieopdracht **B97EI704**

Projectinformatie

Projecttitel

Fragment penetration in composite plates

Projectnummer TNO-PML

014.10686

Omschrijving programma

Verwerven van kennis over de eindballistische aspecten van nieuwe composietmaterialen, die gebuikt worden in moderne vliegtuigen, teneinde beter letaliteits- en kwetsbaarheidsstudies aan moderne vliegtuigen te kunnen uitvoeren.

Planning programma (tijdspad)

In 1997 is een literatuurstudie uitgevoerd welke composieten in moderne vliegtuigen te verwachten zijn. Aan de hand hiervan zijn in 1998 eindballistiche experimenten op deze composieten uitgevoerd. De resultaten worden in dit rapport gepresenteerd.

Projectbegeleider defensie

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Projectleider TNO-PML

Ir. E. van Meerten

Communicatie

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Contents

1 Introduction

Due to their relatively high strength-to-weight ratios, compared to aluminium alloys, as well as other advantages such as good corrosion resistance, the application of composite materials in future aircraft is growing fast, [1]. However, the effect of composites on the vulnerability of fighter aircraft is not yet fully understood. One of the recommendations in The Live Fire testing report of the F-22, [2] to improve vulnerability assessment tools is:

' Focus on ways to understand fully the response of F-22 composite materials to ballistic damage, and develop and exercise analysis tools that can handle large-scale damage effects'.

The Weapon Effectiveness Research Group of the TNO Prins Maurits Laboratory (TNO-PML) has been conducting vulnerability assessments on various targets for a number of years, using their own developed simulation tool, called TARVAC (TARget Vulnerability Assessment Code). Some of the targets are fixed-wing aircraft and helikopters. TARVAC uses different modules for the final vulnerability assessment of the target, expressed in the probability of a kill of the target, given a hit or burst of a projectile or warhead.
One of these modules computes how deep a projectile or fragment can penetrate the target and what damage is inflicted on the target and its internal components. The computations are based on so-called penetration relationships. These relationships compute whether a projectile/fragment, given its shape, mass, impact velocity and impact angle, is able to penetrate a certain thickness of material. Furthermore, if penetration has taken place, the residual velocity and mass of the projectile/fragment is computed. Needless to say that the penetration capability strongly depends on the type of material. Data is available on some thirty different materials (most of them metals) that are input for the penetration relationships.
For typical composite materials, which will be used for future aircraft structures, this data is lacking to perform reliable computations. Therefore a programme was started to conduct firing trials against composite plates with various thicknesses to fill this gap. The first step was to derive relationships for the determination of the residual velocity after penetration of the composite plates. This investigation was conducted under assignments A95KLu523 (Weapon/ammunition effectiveness against aircraft) and B97EI704 (Vulnerability of composite aircraft structures), respectively.

Before the firing trials started, the DERA (Defence Evaluation and Research Agency)/Farnborough (UK) expressed their interest in participating in the programme. Furthermore, the Platform Technology Research Group of TNO-PML was also interested in participating in these trials, since they are investigating the ballistic resistance of composite plates when used as protective measures for radar masts on board rigates (assignment B97EI706, Blast resistance of composite ship structures).

Therefore, it was decided to conduct the trials against two types of typical aircraft composite plates; one type being defined by TNO-PML and the other one by DERA/Farnborough, and against typical composite plates which could be used to protect the radar mast of a ship. The firing trials took place at the Laboratory for Ballistic Research of TNO-PML.

Chapter 2 gives a description of the composite materials. The firing programme is addressed in Chapter 3. Chapter 4 gives an overview of the main results of the trials. Some conclusions and recommendations can be found in Chapter 5.

2 Test description

The purpose of this study is to derive relationships between impact velocities and residual velocities after penetration of composite plates as a function of the plate thickness, impact angle, fragment mass, fragment shape, fragment material and plate material. Therefore, firing trials were conducted with several combinations of plate thicknesses and plate materials, impact velocities, impact angles, fragment masses, fragment shapes and fragment materials.

2.1 Plate material

The composite plates, which were defined by TNO-PML together with the National Aerospace Laboratory in the Netherlands, were of the type HTA/977-2. The fibres were laid in a 0°/45°/90°/-45° position. Four layers of fibres result in a plate of approximately 1 mm thickness. Three different plate thicknesses were produced: 2.1 mm, 4.2 mm and 8.5 mm, respectively.
The plates defined by DERA/Farnborough were of the type Hercules AS4/3501, which has woven fibres. These plates had a wider range in thickness, viz. 3.2 mm, 6.4 mm, 9.5 mm, 12.7 mm, 17.1 mm and 25.4 mm, respectively.
The plates used as protection on board ships consisted of E-glass fibre & vinyl ester. The glass fibres were laid in a 45°/-45°/0°/45°/-45°/0°/45°/-45° position. Derakane 8084 epoxy vinyl ester resin is used as matrix material. Three different plate thicknesses were produced: 5 mm, 9 mm and 23 mm, respectively.

2.2 Fragment description

Three different types of fragments were used for the firing trials: steel so-called Fragment Simulation Projectiles (FSPs), steel cubes and tungsten cubes. FSPs are regular-shaped projectiles (see Figure 1) with a penetration capability that is representative of a fragment with the same mass as the FSP.

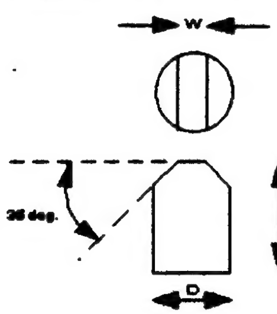

Figure 1: *Sketch of an FSP.*

Table 1 shows which FSPs with the following masses and dimensions were used.

Table 1: The masses and dimensions of the FSPs.

Mass (grams)	D (mm)	H (mm)	W (mm)
0.486	4.05	4.60	2.00
1.1	5.38	6.35	2.55
2.8	7.7	8.7	3.4
5.3	9.1	11.4	4.2
13.4	12.9	14.7	5.7
39	18.2	20.1	9.4

The tungsten cubical fragment had a mass of 1.53 grams and the steel cubical fragment had a mass of 3.38 grams.

2.3 Firing overview

Table 2 shows an overview of the firings conducted on the HTA/977-2 plates.

Table 2: The firings with the FSPs and cubes on the HTA/977-2 plates.

Mass of FSP (grams)	Plate thickness (mm)	Impact angle	# of firings
0.486	2.1	0	10
0.486	4.2	0	9
0.486	4.2	60	6
0.486	8.5	0	10
1.1	2.1	0	17
1.1	2.1	60	4
1.1	4.2	0	13
1.1	4.2	60	5
1.1	8.5	0	12
5.3	2.1	0	15
5.3	4.2	0	9
5.3	8.5	0	7
13.4	2.1	0	5
13.4	4.2	0	7
13.4	8.5	0	8
Mass of cubes (grams)	**Plate thickness (mm)**	**Impact angle**	**# of firings**
1.53 (tungsten)	2.1	0	14
1.53 (tungsten)	4.2	0	4
1.53 (tungsten)	8.5	0	7
3.38 (steel)	2.1	0	5
3.38 (steel)	4.2	0	5
3.38 (steel)	8.5	0	5

Table 3 shows an overview of the firings conducted on the Hercules AS4/3501 plates.

Table 3: The firings with the FSPs and cubes on the Hercules AS4/3501 plates.

Mass of FSP (grams)	Plate thickness (mm)	Impact angle (NATO deg.)	# of firings
1.1	3.2	0	3
1.1	6.4	0	3
1.1	9.5	0	4
1.1	12.7	0	3
1.1	15.9	0	3
2.8	3.2	0	5
2.8	6.4	0	4
2.8	9.5	0	4
2.8	12.7	0	6
2.8	15.9	0	3
5.3	3.2	0	5
5.3	6.4	0	4
5.3	9.5	0	4
5.3	12.7	0	4
5.3	15.9	0	5
Mass of cubes (grams)	**Plate thickness (mm)**	**Impact angle (NATO deg.)**	**# of firings**
1.53 (tungsten)	3.2	0	5
1.53 (tungsten)	6.4	0	6
1.53 (tungsten)	9.5	0	13
1.53 (tungsten)	12.7	0	8
1.53 (tungsten)	15.9	0	7
1.53 (tungsten)	25.4	0	3
3.38 (steel)	3.2	0	5
3.38 (steel)	6.4	0	6
3.38 (steel)	9.5	0	5
3.38 (steel)	12.7	0	5
3.38 (steel)	15.9	0	5
3.38 (steel)	25.4	0	3

Table 4 shows an overview of the firings conducted on the E-glass fibre & vinyl ester plates.

Table 4: The firings with the FSPs ont the E-glass fibre & vinyl ester plates.

Mass of FSP (grams)	Plate thickness (mm)	Impact angle (NATO deg.)	# of firings
1.1	5	0	4
1.1	9	0	4
1.1	5	60	5
5.3	5	0	7
5.3	9	0	7
5.3	23	0	8
13.4	5	0	5
13.4	9	0	5
13.4	23	0	6
39	5	0	4
39	9	0	4
39	23	0	4

3 Results

The code TARVAC computes the residual velocity and mass of the fragments after perforation using the THOR equations (eq. 1), which are based on earlier firing trials with fragments on plates of different materials, [3]. The THOR equation for the residual velocity is:

$$V_r = V - 10^{c_1}\left[t.S_n \frac{m^{2/3}}{\rho_f^{2/3}}\right]^{c_2} m^{c_3} \left(1/\cos\delta \right)^{c_4} V^{c_5} \quad (1)$$

In these THOR equations the so-called shape number S_n can be determined using Equation 2.

$$\overline{S}_n = \frac{\overline{A}_f}{Vol^{2/3}} = \rho_f^{2/3}\frac{\overline{A}_f}{m^{2/3}} \quad (2)$$

in which:

m	impact fragment mass [grains]
V	impact velocity [ft/s]
δ	impact angle [°NATO]
A_f	averaged presented area of the fragment [ft^2]
t	plate thickness [in]
c_i	constants (1 t/m 5)
m_r	residual mass [grains]
V_r	residual velocity [ft/s]
Vol	volume (ft^3)
ρ_f	fragment density

These equations are only valid within a limited velocity area. Especially close to the ballistic limit velocity, the THOR equations are not valid.

For this study, the same type of relationship for the residual velocity has been used. So for all three composite materials, the constants c_1 to c_5 had to be determined to be able to compute the residual velocity for the different composite plates. To determine these constants, many firing trials were conducted, see Chapter 2. The results of these firings are presented in annexes A, B and C for the HTA/977-2 plates, the Hercules AS4/3501 plates and the E-glass fibre & vinyl ester plates, respectively. As can be seen from the tables presented in Chapter 2 and the results in the annexes, the number of firings differ from plate to plate. The results of the firings close to the ballistic limit velocity were not taken into account, because the THOR equations are not valid in the region of these velocities. Some of the firings resulted in complete out of range values. So for the determination of the constants, these values were omitted. All experimental data used are included in the figures shown in the annexes. Using the least square method for each type of composite material, the constants c_1 to c_5 were determined. For each composite material a

relationship is found between the impact velocity and the residual velocity as a function of the impact angle, fragment mass, fragment shape, fragment material and the plate thickness. The results are given in Table 5.

Table 5: The constants c_1 to c_5 to determine the residual velocity after perforation.

	C_1	C_2	C_3	C_4	C_5
HTA/977-2	4.765	0.946	-1.016	0.832	0.376
Hercules AS4/3501	5.180	0.962	-1.072	0.852	0.275
E-glass fibre & vinylester	5.743	1.040	-1.121	0.487	0.203

As can be seen from the results presented in annex A, the determined relationships fit well with the experimental data for all the firings on every type of composite material.

Due to the form of the FSPs, these do not tumble during flight, and therefore will always strike the plates in the same way. On the other hand, the cubes may tumble. During the experiments, photographs were taken of the attitude of the cubic fragments just before impact on the plate. Most of the cubes tumbled over approximately 15°. Therefore the results of the cubes are presented for minimum presented area, maximum presented area and presented area of a cube that has tumbled over 15°. As can be seen a large scatter is found between the residual velocities determined with a minimum and maximum presented area. The derived function fits very well for the cubes with the presented area of a cube that has tumbled over 15°. This corresponds with the photographs taken.

The ballistic resistance of the composite plates is compared with the ballistic resistance of steel and aluminium plates. Figure 3.1 shows the residual velocity as a function of the impact velocity for an FSP of 1.1 grams and 0° NATO impact angle for the three composite plates, an aluminium and a steel plate, all with the same thickness of 3.5 mm. As can be seen, the ballistic resistance is lower for the composite plates. For an impact velocity of 1000 m/s, an aluminium plate with a thickness of approximately 55-60% of the thickness of a composite plate has a comparable ballistic resistance. For steel plates, the thickness has to be approximately 20-25% of the composite plate thickness to attain a comparable ballistic resistance.

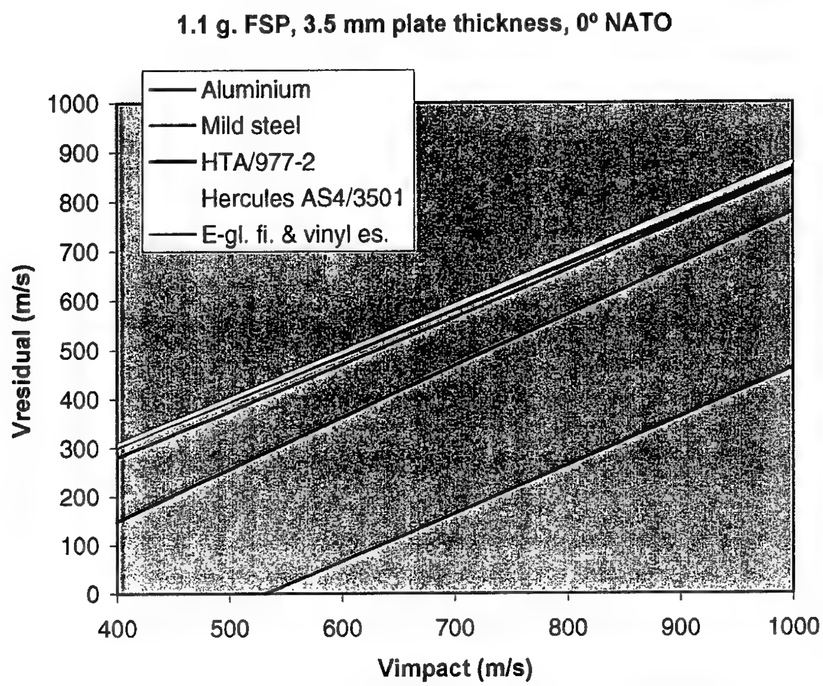

Figure 2: *The residual velocity as a function of the impact velocity for aluminium, steel and composite plates.*

4 Conclusions

As can be seen from the results presented in the annexes, the residual velocity of the fragment after perforation of a composite plate determined with the derived relationships fits the experimental values well. Only close to the ballistic limit velocity the derived relationship is not valid. Therefore the derived relationships can only be used when the residual velocities are greater than 200 m/s.

More experiments have to be performed to determine the ballistic limit velocity for the composite plates. With the values for the ballistic limit velocity and the experimental data already collected, the relationship for the residual velocity can be improved for the residual velocities within the range of 0 to 200 m/s.

The ballistic resistance of composite plates is not as good as aluminium and steel plates with the same thickness. For an impact velocity of 1000 m/s, aluminium plates and steel plates with a thickness of approximately 55-60% and 20-25% respectively of the thickness of a composite plate have a comparable ballistic resistance.

The purpose of this study was to derive a function for the residual velocity after perforating composite plates for use in vulnerability studies. For a complete overview and understanding, the sizes of the damage areas have to be described as well. Therefore this study is only the first step in analysing the ballistic behaviour of composite materials to get a suitable relationship for vulnerability and/or lethality analysis.

Another step which has to be taken is to determine the damage pattern inflicted on the composite plates after fragment perforation. This means that not only the hole size has to be determined, but also the delamination area, which will influence the residual strength of the plate.

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6 Authentication

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Group leader

P.W. Doup
Author

Annex A Results for the HTA/977-2 plates

This annex shows the results of the firings on the HTA/977-2 plates. Figures A.1 to A.4 present the results for the 0.486 gram, 1.1 gram, 5.3 gram and 13.4 gr FSPs, respectively, including the function fits.

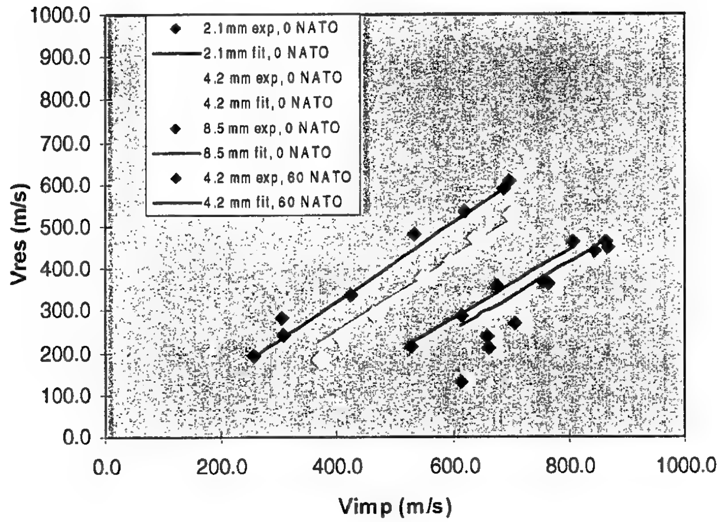

Figure A.1: Results of 0.486 g. FSPs on the HTA/977-2 plates.

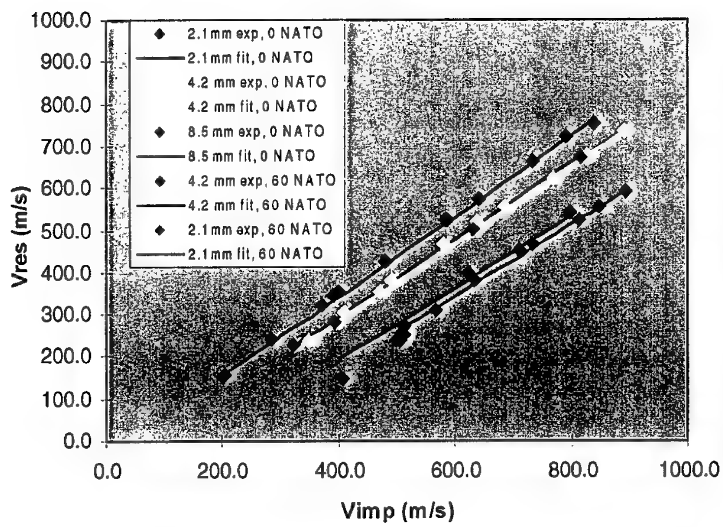

Figure A.2: Results of 1.1 g. FSPs on the HTA/977-2 plates.

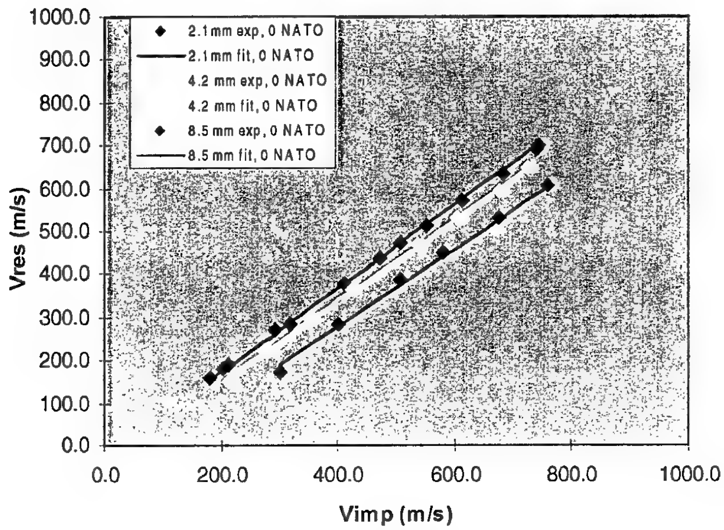

Figure A.3: Results of 5.3 g. FSPs on the HTA/977-2 plates.

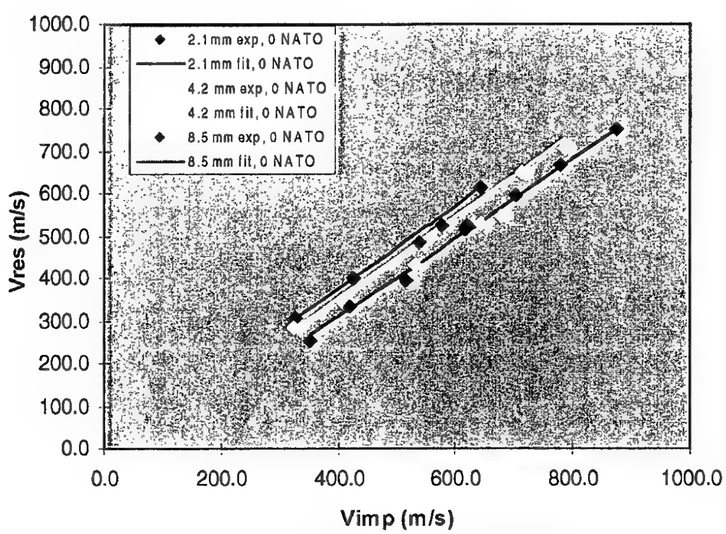

Figure A.4: Results of 13.4 g. FSPs ont the HTA/977-2 plates.

Figures A.5 and A.6 present the results for the 1.51 gram tungsten cubes and the 3.38 gram steel cubes, respectively. In these figures the results of the cubes are presented for minimum presented area, maximum presented area and presented area of a cube that hastumbled over 15°. As can be seen, a large scatter is found between the residual velocities determined with a minimum and maximum presented area. The derived function fits very well for the cubes with the presented

area of a cube that has tumbled over 15°. This corresponds with the photographs taken of the cubes just prior to impact.

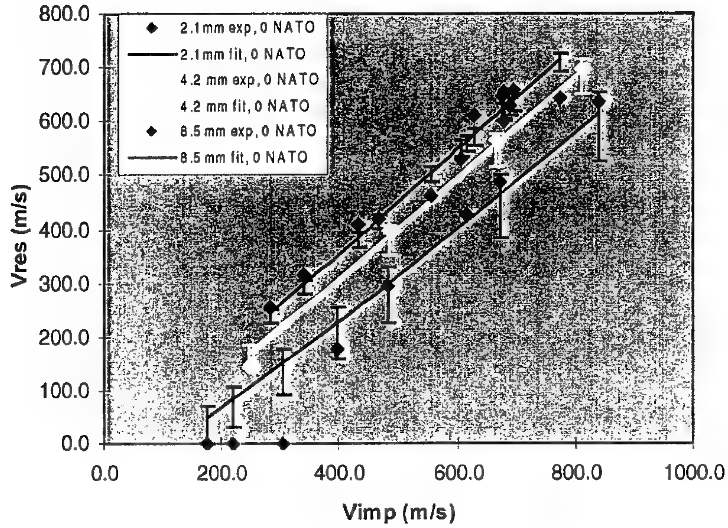

Figure A.5: Results of 1.53 g. cubes on the HTA/977-2 plates.

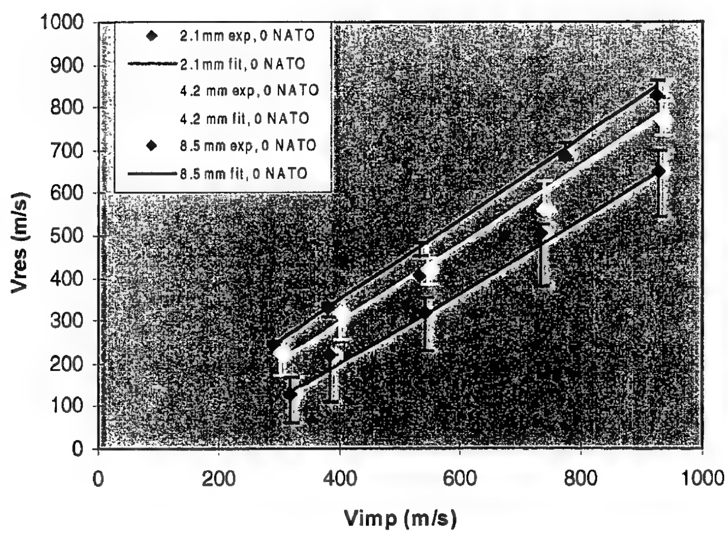

Figure A.6: Results of 3.38 g. cubes on the HTA/977-2 plates.

Annex B Results for the Hercules AS4/3501 plates

This annex shows the results of the firings on the Hercules AS4/3501 plates. Figures B.1 to B.3 present the results for the 1.1 gram, 2.85 gram and 5.3 gr FSPs, respectively, including the function fits.

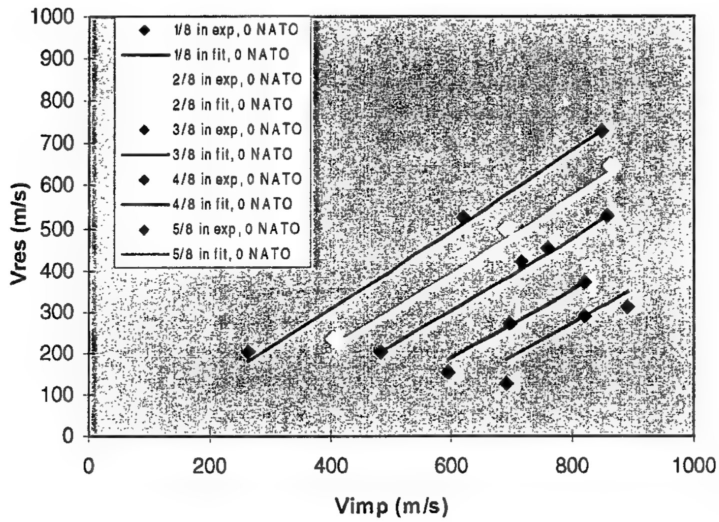

Figure B.1: Results of 1.1 g. FSPs for the Hercules AS4/3501 plates.

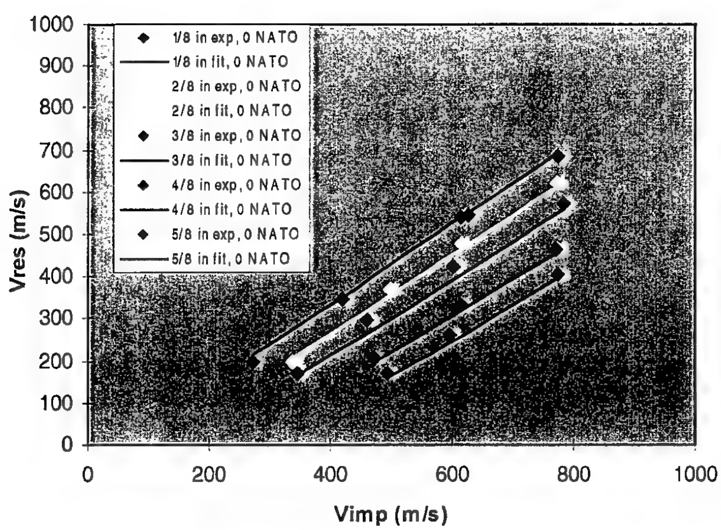

Figure B.2: Results of 2.85 g. FSPs on the Hercules AS4/3501 plates.

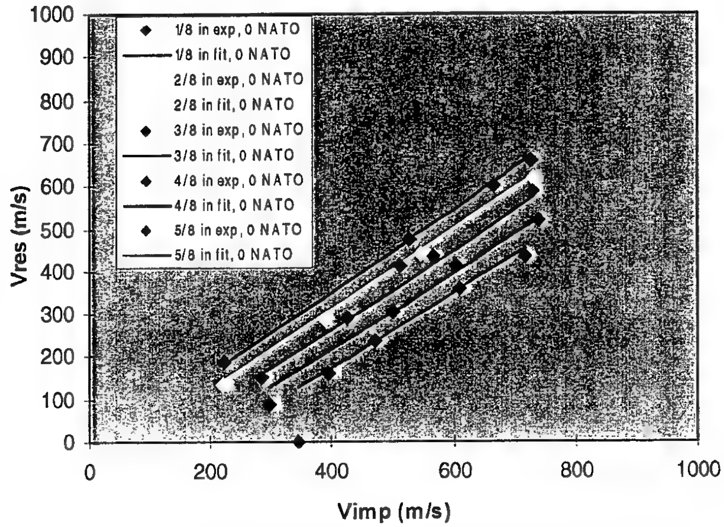

Figure B.3: Results of 5.3 g. FSPs on the Hercules AS4/3501 plates.

Figures B.4 to B.7 present the results for the 1.51 gram tungsten cubes and the 3.38 gram steel cubes. In these figures the results of the cubes are presented for minimum presented area, maximum presented area and presented area of a cube that has tumbled over 15°. As can be seen, a large scatter is found between the residual velocities determined with a minimum and maximum presented area. The derived function fits very well for the cubes with the presented area of a cubethat has tumbled over 15°. This corresponds with the photographs taken of the cubes just prior to impact.

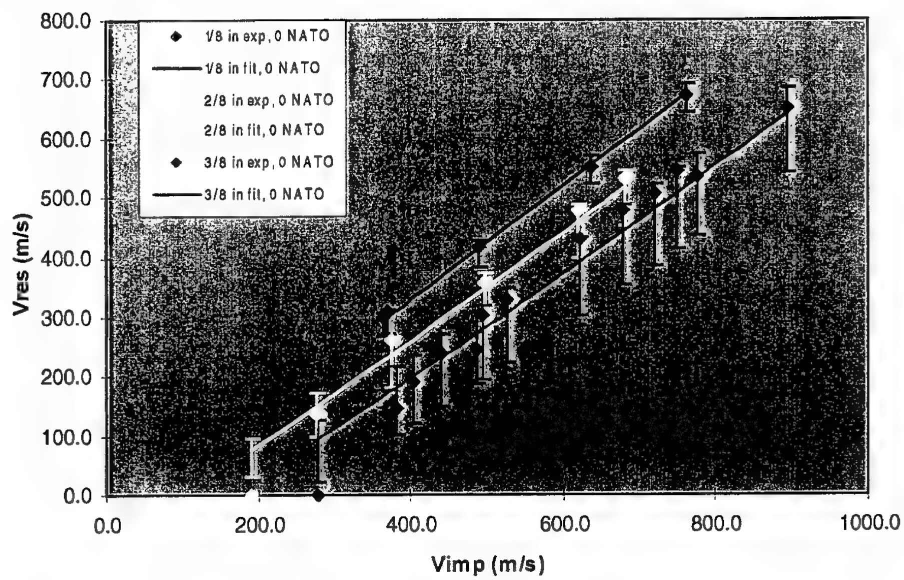

Figure B.4: Results of 1.53 g. cubes on the Hercules AS4/3501 plates.

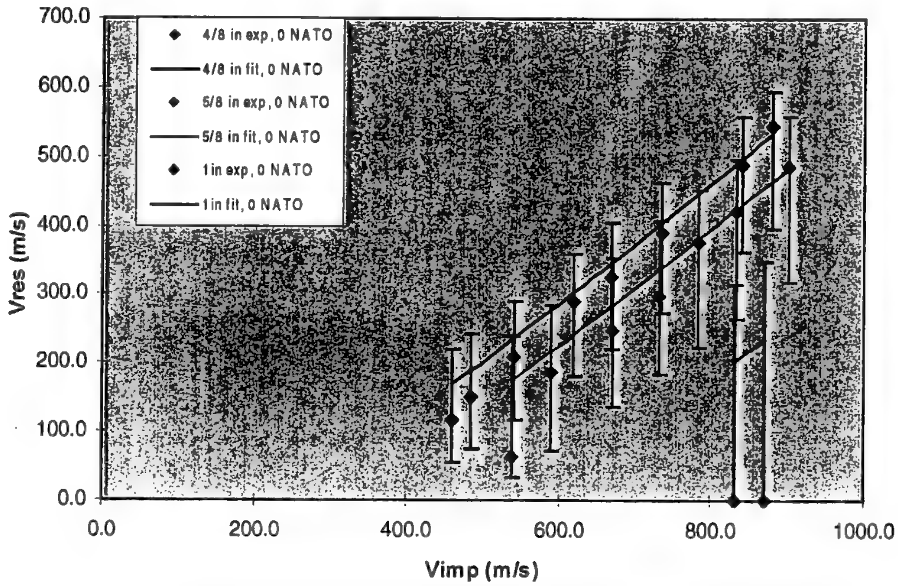

Figure B.5: Results of 1.53 g. cubes on the Hercules AS4/3501 plates.

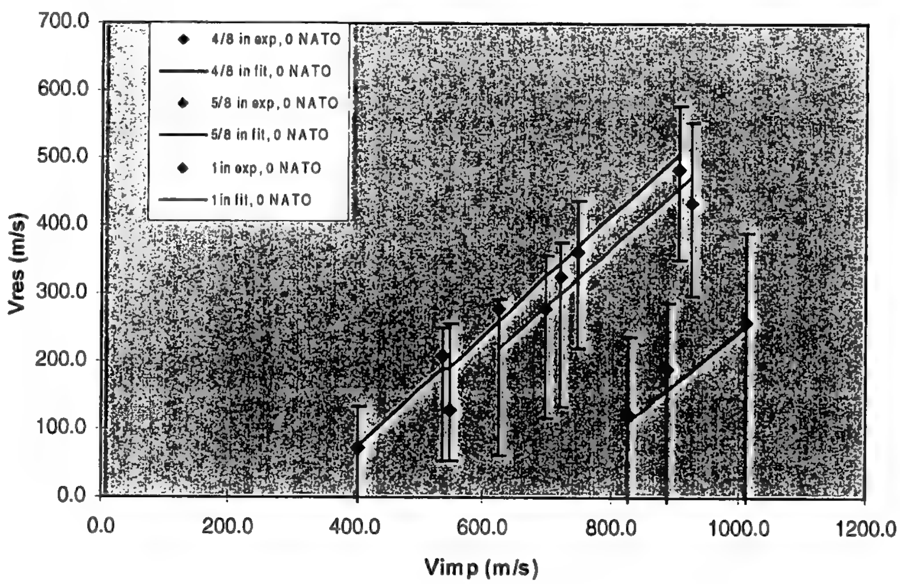

Figure B.6: Results of 3.38 g. cubes on the Hercules AS4/3501 plates.

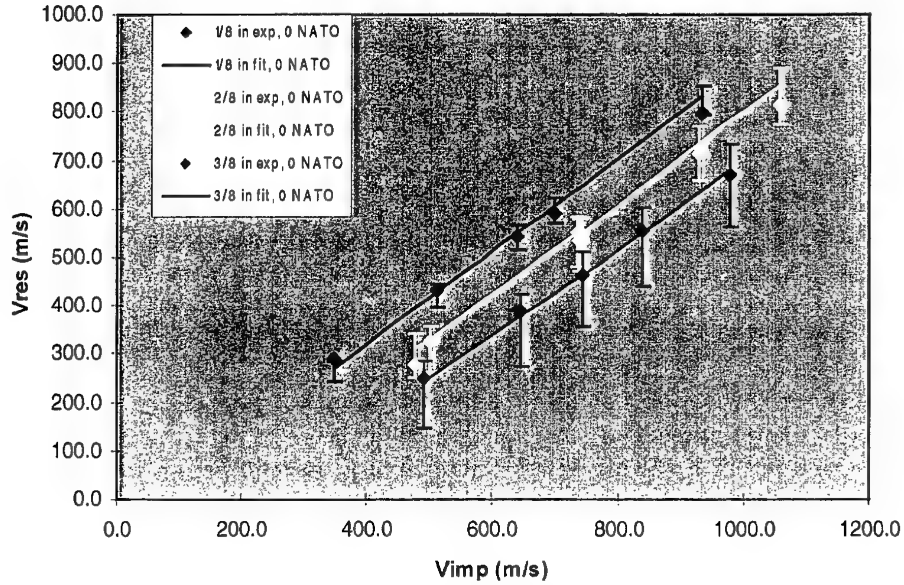

Figure B.7: Results of 3.38 g. cubes on the Hercules AS4/3501 plates.

Annex C Results for the E-glass fibre & vinyl ester plates

This annex shows the results of the firings on the E-glass fibre & vinyl ester plates. Figures C.1 to C.4 present the results for the 1.1 gram, 5.3 gr, 13.4 gram and 39 gram FSPs, respectively, including the function fits.

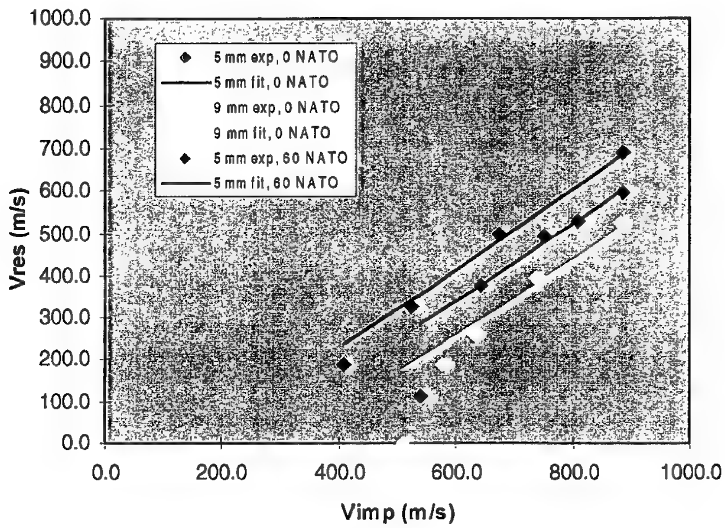

Figure C.1: Results of 1.1 g. FSPs on the E-glass fibre & vinyl ester plates.

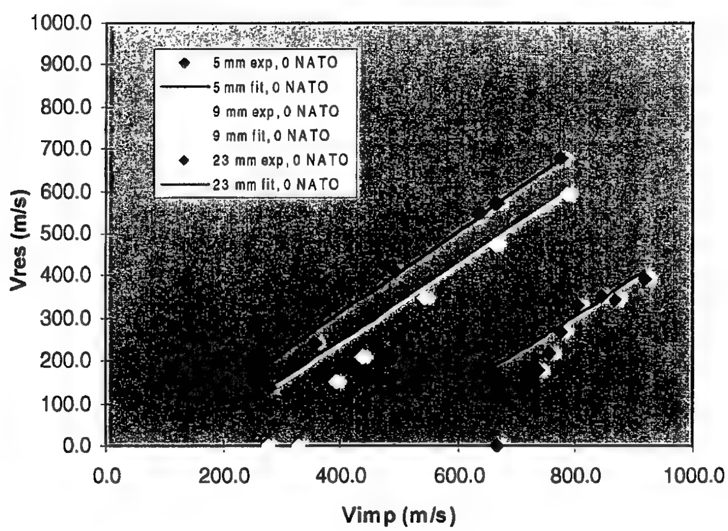

Figure C.2: Results of 5.3 g. FSPs on the E-glass fibre & vinyl ester plates.

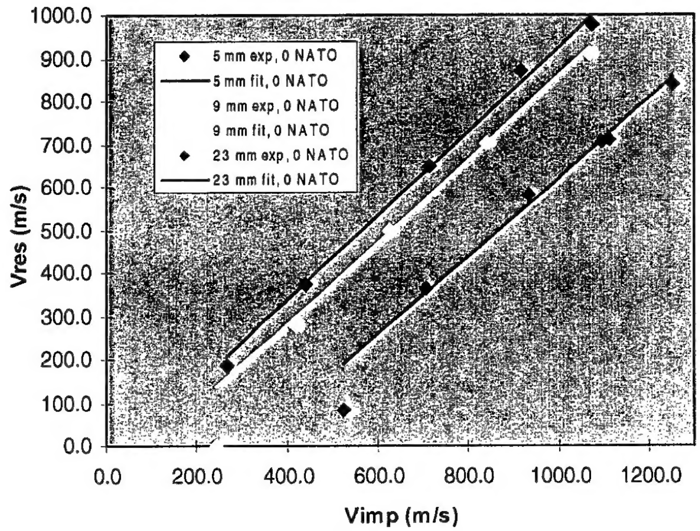

Figure C.3: Results of 13.4 g. FSPs on the E-glass fibre & vinyl ester plates.

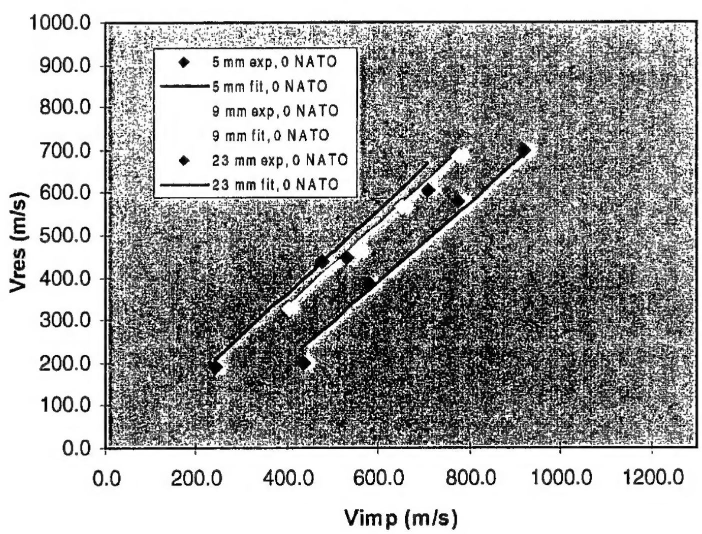

Figure C.4: Results of 39 g. FSPs on the E-glass fibre & vinyl ester plates.

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Due to their relatively high strength-to-weight ratios, compared to aluminium alloys, as well as other advantages such as good corrosion resistance, theapplication of composite materials in future aircraft is growing fast, [1]. However, the effect of composites on the vulnerability of fighter aircraft is not yet fully understood. The first step is to derive relationships for the determination of the residual velocity after penetration of the composite plates. Therefore a programme was started to conduct firing trials on three different types of composite plates of various thicknesses. This report presents the results of the firing trials and the derived relationships for the determination of the residual velocity after perforation of the composite plates.

16. DESCRIPTORS

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Airplanes	Airplanes
Kill probabilities	Kill probabilities
Vulnerabilities	Vulnerabilities
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Penetration	Penetration

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